Energy Loss of Hard Partons in Nuclear Matter

Urs Achim Wiedemann[a]

[a] Theory Division, CERN, CH-1211 Geneva 23

We report on recent calculations of the medium-induced gluon radiation off hard partons. The employed path-integral formalism reduces in limiting cases to the main "jet quenching" results of the existing literature. Moreover, it describes destructive interference effects between medium-independent and medium-induced radiation amplitudes. These affect the angular distribution and L-dependence of the medium-induced gluon bremsstrahlung spectrum significantly.

1. Introduction

At this conference, the PHENIX and STAR Collaborations have presented hadronic transverse momentum spectra in central Au+Au collisions at $\sqrt{s_{\rm NN}} = 130$ GeV[1,2]. In comparison to rescaled $p + \bar{p}$ UA1 reference data, these spectra show a depletion at high transverse momentum (2 GeV $< p_\perp <$ 6 GeV). This may be the first experimental indication for jet quenching [3], predicted by Gyulassy and Wang [4] a decade ago.

In general, hadronic transverse momentum spectra contain both a soft and a hard physics component. The hard component, which dominates at sufficiently high $p_\perp$, can be calculated by convoluting the incoming parton distributions with partonic cross sections. Parton fragmentation functions parametrize how the partons produced in hard processes translate into final state hadrons. Thus, the origin of any medium-dependence of high-$p_\perp$ transverse momentum spectra has to be traced back to either i) nuclear modifications of the initial state (e.g. nuclear shadowing) or ii) medium-induced changes of the final state parton fragmentation. While information about nuclear shadowing can be obtained from other observables (e.g. DIS in e-A), the study of the medium-dependence of parton fragmentation functions $D_q^h(z)$ is still in its infancy. Here, we review recent calculations [5–11] of the radiative energy loss off hard partons which aim at describing the medium-induced shift in the energy of the fragmenting parton. For a complementary approach, see Ref. [12].

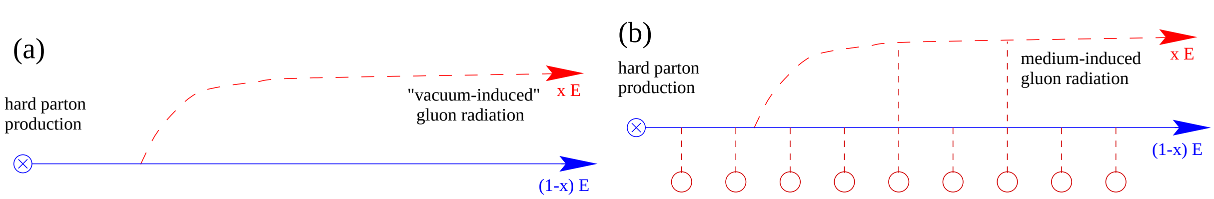

Figure 1. The fragmentation of a hard quark via gluon radiation (a) outside and (b) inside a nuclear environment.

2. Medium-induced Gluon radiation

Fig. 1(a) shows a typical building block of the DGLAP evolution equation. This gluon radiation shifts the energy of the quark by a factor $1-x$. To describe medium-induced changes of such partonic fragmentation patterns, we consider multiple scattering contributions, see Fig. 1(b). For the Gyulassy-Wang model which mimicks the nuclear medium by a set of static coloured scattering potentials, these scattering contributions were calculated recently by several groups [5–11]. All published results are limiting cases of the following expression for the medium-induced gluon radiation cross section off a hard quark [10]:

$$\frac{d^3\sigma}{d(\ln x)\, d\mathbf{k}_\perp} = \frac{\alpha_s}{(2\pi)^2}\,\frac{1}{\omega^2}\, N_C\, C_F\, 2\mathrm{Re} \int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l\, e^{-\epsilon|y_l|-\epsilon|\bar{y}_l|} \\ \times \int d\mathbf{u}\, e^{-i\mathbf{k}_\perp\cdot\mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^\infty d\xi\, n(\xi)\,\sigma(\mathbf{u})}\, \frac{\partial}{\partial \mathbf{y}}\cdot\frac{\partial}{\partial \mathbf{u}}\, \mathcal{K}(\mathbf{y}=0, y_l; \mathbf{u}, \bar{y}_l|\omega)\,. \tag{1}$$

Here, x denotes the energy fraction of the hard quark, carried away by the gluon, and $\mathbf{k}_\perp$ its transverse momentum. Information about the nuclear medium enters via the combination $n(\xi)\,\sigma(\mathbf{r})$, where $n(\xi)$ determines the density of scattering centers in the medium, and the dipole cross section $\sigma(\mathbf{r}) \propto \int d\mathbf{q}_\perp\, |a_0(\mathbf{q}_\perp)|^2\,(1-e^{-i\mathbf{q}_\perp\cdot\mathbf{r}})$ contains configuration space information on the strength of a single elastic differential scattering cross section $|a_0(\mathbf{q}_\perp)|^2$. $\mathcal{K}$ denotes the two-dimensional path-integral [5]

$$\mathcal{K}(\mathbf{r}(y_l), y_l; \mathbf{r}(\bar{y}_l), \bar{y}_l|\omega) = \int \mathcal{D}\mathbf{r}\, \exp\left[\int_{y_l}^{\bar{y}_l} d\xi \left(i\frac{\omega}{2}\dot{\mathbf{r}}^2 - \frac{1}{2}n(\xi)\sigma\left(\mathbf{r}\right)\right)\right]\,, \tag{2}$$

3. Opacity Expansion

In relativistic heavy ion collisions, hard partons typically propagate over distances $L = 1-10\times\lambda_{\mathrm{mfp}}$ inside the excited nuclear medium. To access this region, we expand the radiation spectrum (1) in powers of opacity $\left(\alpha_s \int_0^L d\xi\, n(\xi)\right)^N$ which is related to an expansion in the number of scattering centers. For arbitrary N, it can be shown that the radiation spectrum (1) interpolates between the classically expected N-fold scattering results in both the coherent ($L\to 0$) and incoherent ($L\to\infty$) limiting cases [10]. For example, up to first order [10]

$$\frac{d^3\sigma(N=0,1)}{d(\ln x)\, d\mathbf{k}_\perp} = \frac{\alpha_s}{\pi^2}\, N_C\, C_F \left(\frac{1}{\mathbf{k}_\perp^2} + \frac{1}{2\,\omega^2}\int_{\Sigma_1} \frac{-\mathbf{k}_\perp\cdot\mathbf{q}_\perp}{Q\, Q_1}\, n_0\, \frac{LQ_1 - \sin(LQ_1)}{Q_1}\right) \\ \Longrightarrow_{\lim_{L\to\infty}} \frac{\alpha_s}{\pi^2}\, N_C\, C_F \left[(1-w_1)\, H(\mathbf{k}_\perp) + n_0\, L \int_{\mathbf{q}_1} \left[H(\mathbf{k}_\perp+\mathbf{q}_\perp) + R(\mathbf{k}_\perp, \mathbf{q}_\perp)\right]\right]\,. \tag{3}$$

Here, $Q = \frac{\mathbf{k}_\perp^2}{2\omega}$, $Q_1 = \frac{(\mathbf{k}_\perp+\mathbf{q}_\perp)^2}{2\omega}$ are transverse energies, the "hard" term $\frac{\alpha_s}{\pi^2}\, N_C\, C_F\, H(\mathbf{k}_\perp)$, $H(\mathbf{k}_\perp) = \frac{1}{\mathbf{k}_\perp^2}$, is the medium-independent contribution of Fig. 1(a) and $\int_{\mathbf{q}_1}$ is a shorthand for integrating over the elastic scattering cross section. Eq. (3) is the incoherent "classical" parton cascade limit of (1): the medium-independent hard term $H(\mathbf{k}_\perp)$ is reduced by the probability w_1 of an additional scattering. With the probability for this scattering,

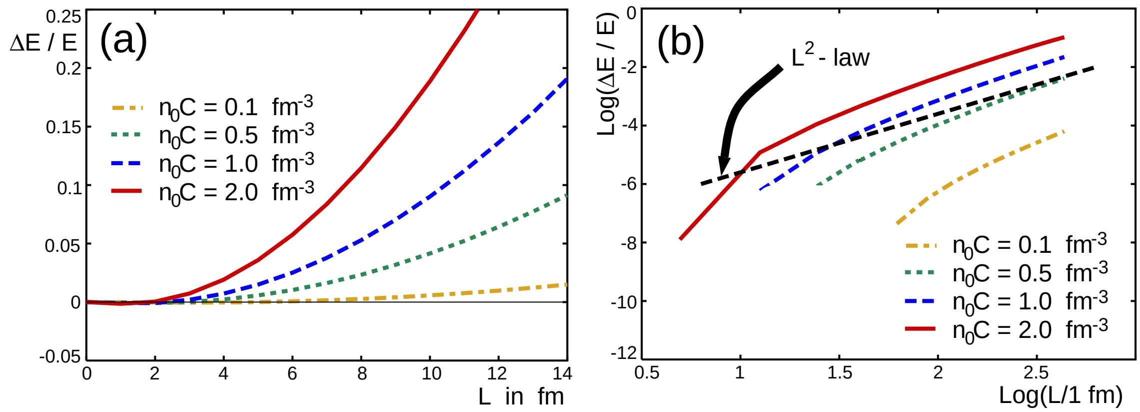

Figure 2. (a) Medium-induced energy loss for a quark of $E = 100$ GeV as a function of the in-medium path length L. (b) The double logarithmic presentation of (a) indicates logarithmic deviations from the BDMPS-L^2-law.

the hard term is shifted in transverse momentum to $H(\mathbf{k}_\perp + \mathbf{q}_\perp)$, and the medium-induced gluon radiation off the hard quark leads to a Gunion-Bertsch radiation term $R(\mathbf{k}_\perp, \mathbf{q}_\perp) = \frac{\mathbf{q}_\perp^2}{\mathbf{k}_\perp^2\,(\mathbf{k}_\perp+\mathbf{q}_\perp)^2}$. The $\mathbf{k}_\perp$-integral of the medium-dependent part of (3) is the GLV-radiation cross section [11]. This lowest order opacity approximation was compared to RHIC data at this conference [3].

4. Dipole Approximation

For large in-medium path length $L \gg \lambda_{\rm mfp}$, the integrand of the radiation cross section (1) is dominated by small transverse distances $\mathbf{u}$ for which $\sigma(\mathbf{u}) \approx C\,\mathbf{u}^2$ up to logarithmic accuracy. In this quadratic approximation, the path-integral $\mathcal{K}$ is that of a harmonic oscillator, and (1) can be reduced to a two-dimensional integral which has to be evaluated numerically [5,10]. The medium dependence enters then via the rescattering parameter $n_0\,C$ which parametrizes the average squared transverse momentum picked up by a hard parton per unit pathlength, $n_0\,C = \frac{\langle \mathbf{q}_\perp^2\rangle}{L}$. This is a measure of the transverse colour field strength seen by a hard parton [10]. In cold nuclear matter, 0.1 fm$^{-3} < n_0\,C < 0.5$ fm^{-3} while in heavy ion collisions, one expects $n_0\,C > 1.0$ fm^{-3} [6,10]. In what follows, we consider the medium-induced deviation of the radiation spectrum, $\sigma_{\rm med}(n_0\,C) = \sigma(n_0\,C) - \sigma(n_0\,C = 0)$. The radiative energy loss ΔE is

$$\frac{\Delta E}{E}(n_0\,C, L, E, \chi) = \int_0^1 dx\, x \int_{|\mathbf{k}_\perp| \le \chi\omega} d\mathbf{k}_\perp \frac{d^3\sigma_{\rm med}}{d(\ln x)\, d\mathbf{k}_\perp}\,. \tag{4}$$

For $\chi = 1$, the $\mathbf{k}_\perp$-integral goes up to the kinematical boundary $\mathbf{k}_\perp = \omega$ and (4) gives the total radiative energy loss. For typical spatial extensions in heavy ion collisions, $L < 10$ fm, we find that the radiative energy loss is very sensitive to the rescattering properties $n_0\,C$ of the medium, see Fig. 2. Its L-dependence satisfies approximately the L^2-law discovered by BDMPS. However, the destructive interference between hard and medium-induced radiation, leads to a delayed onset of any radiative energy loss: ΔE in Fig. 2 turns negative for $L < 2$ fm. This increases the fraction of hard partons whose in-medium path length is too small to result in a significant medium-dependence ("corona effect").

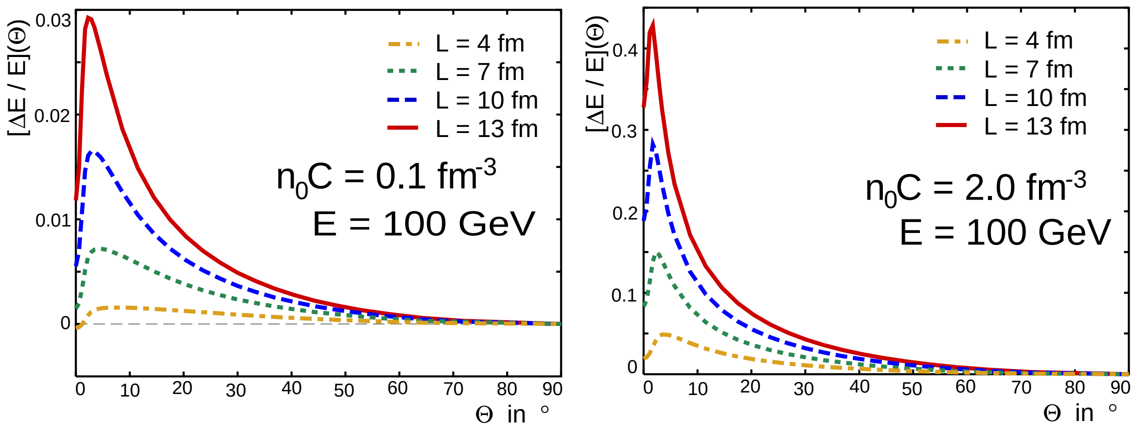

Figure 3. The medium-induced deviation of the energy radiated outside a finite jet opening angle Θ has a maximum at finite angle.

The χ-dependence of (4) translates into an opening angle and allows to calculate radiative energy loss inside a finite jet cone. While the total energy radiated outside a finite angle Θ decreases monotonously with increasing opening angle Θ, this is not the case for the medium-induced deviation obtained from (4) and $\sigma_{\rm med}(n_0\, C) = \sigma(n_0\, C) - \sigma(n_0\, C = 0)$. Medium-induced multiple scattering broadens the medium-independent term $\sigma(n_0\, C = 0) \propto \frac{1}{\mathbf{k}_\perp^2} \to \frac{1}{(\mathbf{k}_\perp + \mathbf{q}_\perp)^2}$. This leads to a maximum of $\Delta E(\Theta)$ for finite opening angle. As a consequence, the $\mathbf{k}_\perp$-integrated energy loss expressions $\Delta E(\Theta = 0)$ presented in previous works are not necessarily upper bounds for the energy lost outside a realistic jet cone.

REFERENCES

1. W.A. Zajc and A. Milov [PHENIX Collaboration], Talks at Quark Matter 2001.
2. J. Harris and J.C. Dunlop [STAR Collaboration], Talks at Quark Matter 2001.
3. X.N. Wang and P. Levai, Talks at Quark Matter 2001.
4. X.-N. Wang and M. Gyulassy, Phys. Rev. **D44** (1991) 3501; M. Gyulassy and X.-N. Wang, Nucl. Phys. **B420** (1994) 583.
5. B.G. Zakharov, JETP Letters **63** (1996) 952; ibidem **65** (1997) 615; **70** (1999) 176.
6. R. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigné and D. Schiff, Nucl. Phys. **B483** (1997) 291; ibidem **B484** (1997) 265.
7. R. Baier, Y.L. Dokshitzer, A.H. Mueller and D. Schiff, Nucl. Phys. **B531** (1998) 403.
8. U.A. Wiedemann and M. Gyulassy, Nucl. Phys. **B560** (1999) 345.
9. R. Baier, Y.L. Dokshitzer, A.H. Mueller and D. Schiff, Phys. Rev. **C60** (1999) 064902.
10. U.A. Wiedemann, Nucl. Phys. **B582** (2000) 409; Nucl. Phys. **B588** (2000) 303; hep-ph/0008241.
11. M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. **B571** (2000) 197, nucl-th/0005032 and nucl-th/0006010.
12. X.F. Guo and X.N. Wang, Phys. Rev. Lett. **85** (2000) 3591 and hep-ph/0102230.